

# Fiber-coupled, high-Q AlGaAs microdisk cavities for chip-based cavity QED

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**Abstract:** Fiber-coupled, high-quality-factor ( $Q > 10^5$ ) AlGaAs microdisks with embedded InAs quantum dots are demonstrated. Microdisk lasers employing evanescent fiber coupling for optical pumping and collection of emission exhibit up to two orders of magnitude improvement in differential efficiency compared to devices probed through normal-incidence, free-space photoluminescence. The fiber taper coupling is also shown to provide an efficient optical channel for studying and manipulating the microcavity-quantum dot system, with in-fiber cavity mode collection efficiencies greater than 20% and cavity loading approaching critical coupling. Progress and current challenges in incorporating such fiber-coupled devices into low temperature experiments for studying coherent interaction between single quantum dot and single cavity mode excitations will be discussed.

Cavity-QED-based devices operating in the strong coupling regime must meet relatively stringent requirements to maintain coherent interactions at the single quantum dot (QD), single-photon level. In particular, the strength of coupling between the quantum dot exciton and the microcavity resonant optical mode,  $g$ , must exceed the quantum dot excitonic dipole decay rate  $\gamma_{\perp}$  and the cavity mode decay rate  $\kappa$ . In addition, an efficient method for injecting photons into the cavity and collecting emitted photons from the cavity is a requirement for applications in linear optics quantum computing and quantum networks. Here, we present results on quantum-dot-containing AlGaAs microdisks with cavity parameters that, under ideal conditions, satisfy the strong coupling condition  $g > (\gamma_{\perp}, \kappa)$ . Furthermore, optical fiber taper waveguides are used to provide an efficient optical channel into the microcavity-quantum dot system, and photoluminescence measurements that utilize these tapers to improve the pump and collection efficiency from room-temperature, microdisk lasers are discussed.

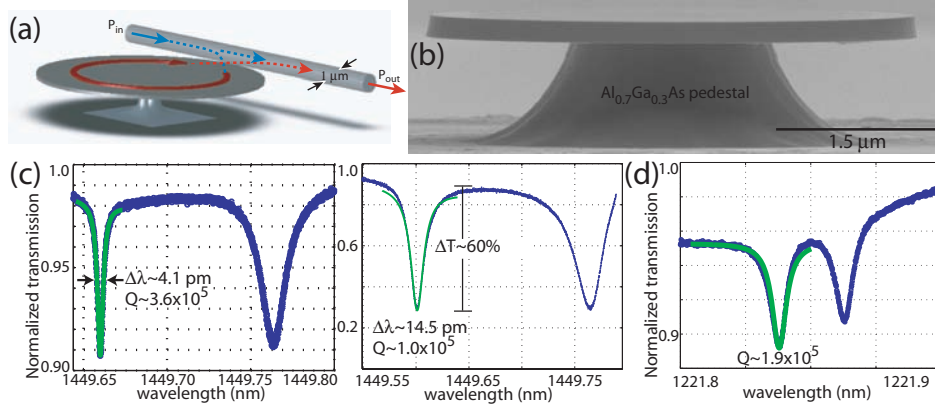


Fig. 1. (a) Schematic of the microdisk-fiber taper coupling geometry. (b) Scanning electron microscope images of fabricated microdisks (the white line to the right of the disk in (c) is a fiber taper). (c) Normalized taper transmission ( $P_{out}/P_{in}$ ) in the 1400 nm wavelength band for large (left) and small (right) taper-cavity separations. (d) Normalized taper transmission in the 1200 nm band,  $\sim 30 \text{ nm}$  detuned from the peak QD emission.

Microdisk cavities (diameter  $D=4.5 \mu m$ ) are fabricated (Fig. 1(b)-(c)) in an AlGaAs-based waveguide containing a single layer of InAs quantum dots-in-a-well (DWELL)[1]. The DWELL material has its ground state emission peak at 1190 nm, and direct passive measurements of optical loss in these structures is performed using an optical-fiber-based probing technique at wavelengths red-detuned from the QD emission (Fig. 1(a,c,d)). This method uses a tapered optical fiber to evanescently couple light to the whispering-gallery modes (WGMs) of the microdisk. Starting with measurements in the 1400 nm band, where the DWELL absorption is expected to be minimal, a cold-cavity quality factor ( $Q$ ) of  $3.6 \times 10^5$  is observed (Fig. 1(c, left)) for a WGM with a predicted effective modal volume  $V_{eff} \sim 6(\lambda/n)^3$ . By decreasing the taper-microdisk separation to  $\sim 200 \text{ nm}$ , the coupling is increased to a depth  $\Delta T \sim 60\%$  for a loaded  $Q \sim 1.0 \times 10^5$  (Fig. 1(c, right)), corresponding to a collection efficiency of emitted photons from the cavity of  $\eta_0 \sim 20\%$ . Furthermore, measurements in the  $\lambda \sim 1.2 \mu m$  band[2] show  $Q$ s of  $1.5\text{--}2.2 \times 10^5$  (Fig. 1(d)), indicating that high quality factors are still achieved at the QD exciton ground-state resonance (this being despite the presence of QD absorption

in this case). Considering cavity QED applications, if these WGM modes with  $\kappa/2\pi \lesssim 1$  GHz were optimally coupled (positioned relative) to a single QD with (typical) ground-state exciton spontaneous emission lifetime of  $\tau_{sp} \sim 1$  ns and low temperature homogeneous broadening of  $\gamma_{\perp}/2\pi \sim 1$  GHz, the corresponding coherent coupling rate between cavity mode photon and QD exciton would be  $g/2\pi \sim 11$  GHz, well within the strong coupling regime.

The high- $Q$ s demonstrated above indicate that room-temperature lasing can be achieved, and indeed, lasing has been observed in both pulsed and continuous wave operation[1], where the optical pumping and collection from the microdisks was performed at normal-incidence, through free-space optics. Here, we consider the use of fiber tapers in photoluminescence (PL) measurements of these devices[2]. Figure 2(a) shows the spectrum obtained in free-space PL measurements where a pump beam at 830 nm (spot size  $\sim 18\mu\text{m}^2$ ) is focused onto a microdisk, and the emitted power is collected at normal incidence with a 0.4 numerical aperture (NA) lens and resolved by an optical spectrum analyzer (OSA). Figure 2(b) shows the spectrum collected when a fiber taper is coupled to the side of the microdisk cavity, under identical free-space pumping conditions. The improved collection efficiency can be quantified by considering the laser differential efficiency above threshold,  $\xi$ . In Figure 2(c)-(d), we see plotted the light-in-light-out (L-L) curves for lasing devices employing free-space and fiber taper collection, respectively. As expected (see Fig. 1(c), for example), the fiber taper loads the cavity and decreases its  $Q$ , causing the threshold pump power to (slightly) increase, but it also improves  $\xi$ , by nearly two orders of magnitude for this device, to a value of  $\xi \sim 1\%$  (when emission into the forward and backward fiber mode are considered). Modifications to the microdisk geometry through adjustments in thickness and radius have been shown to better match the effective index of the WGMs to that of the fundamental silica fiber taper waveguide mode, and measurements in similar *silicon* microdisks have resulted in cavity loading  $> 90\%$  overcoupled. Similar modifications to the AlGaAs microdisk geometry would correspondingly result in an external fiber taper collection efficiency of  $\eta_0 > 95\%$ .

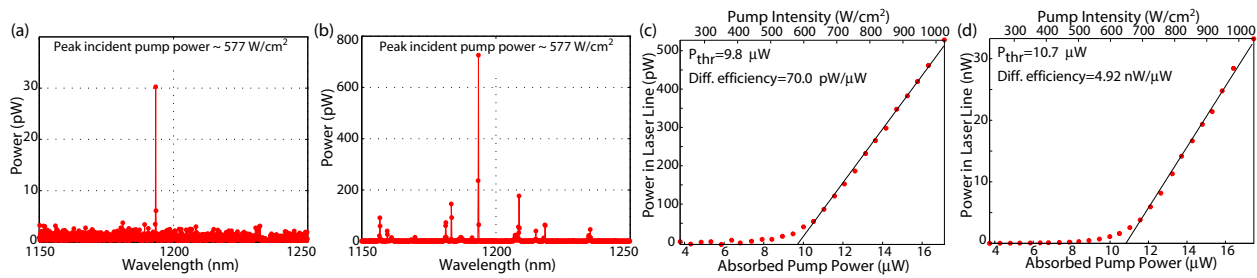


Fig. 2. (a)-(b) Collected spectrum in (a) free-space and (b) fiber taper configurations for a QD-containing microdisk that is pumped with  $\sim 580 \text{ W}/\text{cm}^2$  of pump beam intensity. (c)-(d) Light-in-light-out (L-L) curves for the same device, where the light out is collected (c) free-space and (d) through the fiber taper.

In addition, we have begun experiments utilizing the fiber paper as a means to inject pump light into the microdisks. Preliminary measurements indicate that significant reductions in the *incident* power delivered to the disk can be obtained when the pump wavelength is resonant with a WGM of the cavity. Microdisk lasers employing this fiber pumping and fiber collection have been demonstrated, and the results will be presented. The application of this work may ultimately lie in low-temperature experiments employing near-resonant optical pumping between states of single QDs. As such, progress towards incorporating fiber-coupled microcavity devices in cryogenic environments will also be discussed.

## References

1. K. Srinivasan, M. Borselli, T. Johnson, P. Barclay, O. Painter, A. Stintz, and S. Krishna, "Optical loss and lasing characteristics of high-quality-factor AlGaAs microdisk resonators with embedded quantum dots," *Appl. Phys. Lett.* **86**, 151106 (2005).
2. K. Srinivasan, A. Stintz, S. Krishna, and O. Painter, "High-efficiency photoluminescence measurements of quantum-dot-containing microdisk cavities using optical fiber tapers," submitted for publication (available at [www.arxiv.org/abs/physics/](http://www.arxiv.org/abs/physics/)) (2005).